TITLE: A Physics Based Broadband Scene Simulation Tool for CCD Assessment

A PHYSICS BASED BROADBAND SCENE SIMULATION TOOL FOR CCD ASSESSMENT

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1. SUMMARY

Assessment of Camouflage, Concealment and Deception (CCD) methodologies is a non trivial problem; conventionally the only method has been to carry out field trials, which are both expensive and subject to the vagaries of the weather. In recent years computing power has increased, such that there are now many research programmes using synthetic environments for CCD assessments. Such an approach is attractive; the user has complete control over the environment parameters and many more scenarios can be investigated.

The UK Defence Evaluation and Research Agency is currently developing a synthetic scene generation tool for assessing the effectiveness of air vehicle camouflage schemes. The software is sufficiently flexible to allow it to be used in a broader range of applications, including full CCD assessment. The synthetic scene simulation system (CAMEO-SIM) has been developed, as an extensible system, to provide imagery within the 0.4 - 14 micron spectral band with as high a physical fidelity as possible. It consists of a scene design tool, an image generator, which incorporates both radiosity and ray-tracing processes, and an experimental trials tool. The scene design tool allows the user to develop a three-dimensional representation of the scenario of interest from a fixed view-point. Target(s) of interest can be placed anywhere within this 3-D representation and may be either static or moving. Different illumination conditions and effects of the atmosphere can be modelled together with directional reflectance effects. The user has complete control over the level of fidelity of the final image. The output from the rendering tool is a sequence of radiance maps which may be used by sensor models, or for experimental trials in which observers carry out target acquisition tasks. The software also maintains an audit trail of all data used to generate a particular image, both in terms of material properties used and the rendering options chosen.

Keywords: Scene Simulation, CCD Assessment, Camouflage, Concealment & Deception

2. INTRODUCTION

All camouflage is a compromise. It is required to match different backgrounds, in different wavebands and at different times of the year. The compromises made in the past were determined by subjective assessment of the visibility of a military asset when viewed against some relevant background. Typically, this assessment was carried out in the visible band only. Two technologies are driving the need for quantitative CCD assessment. Firstly, sensors now operate throughout a large part of the electromagnetic spectrum and it is likely that future sensors will place even greater demands on camouflage design by requiring exact spectral matches. Secondly, new techniques and materials offer the potential of increased effectiveness of camouflage against sensor threats. Cost-effective and quantitatively correct assessment of these techniques and materials is essential for future system survivability.

Synthetic scene generation offers a viable alternative to field trials for the quantitative evaluation of camouflage. We are developing a physics based, broadband, scene simulation toolset called CAMEO-SIM that enables the quantitative evaluation of both current and future camouflage. The same toolset may also be used to assess concealment and deception methodologies.

3. STRUCTURE OF THE PAPER

Section 4, provides an overview of the components that make up the CAMEO-SIM toolset. Section 5 reviews the verification tests that have been carried out to date, section 6 describes the validation programme and section 7 presents conclusions.

4. OVERVIEW OF CAMEO-SIM

The goal of the CAMEO-SIM system is to produce synthetic, high resolution, physically accurate radiance images of target vehicles in operational scenarios, at any wavelength between 0.4 and 14 microns. The main components of the system are shown schematically in Figure 1. These are described in detail elsewhere [1]. The software was developed with a scaleable rendering kernel in which imagery can be produced at different fidelities and frame rates depending on the image application and wavelength of operation.

The lowest fidelity mode is real-time and can be used to develop and preview the scene before it is passed to a scaleable two-pass rendering kernel that can produce high quality image streams using BRDF capable radiosity and ray-tracing algorithms. The first pass computation models the radiative transfer between extended surfaces; ie., it models 'soft' shadow effects. The second pass is a ray tracer to model the effect of point sources - it models the 'hard' shadows. The images produced from these algorithms are then used in the camouflage assessment process. The user has detailed control of the parameters used in the calculations.

The rendering equations solved during real-time operations are termed 'local' rendering equations. The term 'local' is used to acknowledge the fact that the radiative interactions in the scene are predefined. In order to run in real-time, approximations are made during the rendering process. These include:

1. the directionality and bi-directionality of the optical properties of materials in the scene are approximated using scalar diffuse optical properties, perhaps with a simple specular parameter added to the reflectivity.
2. global illumination effects are not accounted for.

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3. geometric occlusion of point and extended sources of radiation is ignored.
4. spectral integration of the optical properties with the atmospherics is reduced to a multiplication of the in-band optical property with the in-band atmospheric term – such an approximation is only valid for spectrally grey materials.
5. the parameterisation of the atmospheric terms is simplified - for example 3D variations in the path radiance and transmittance are ignored.
6. polygon budgets are restricted - which means that the structure of complex objects such as vehicles or trees has to be simplified.

To assess the effectiveness of camouflage schemes, especially on helicopters flying at low level using trees as natural cover, these real-time approximations can impact critically on the final computed air vehicle contrast. Therefore higher fidelity, non real-time computations must be used. The CAMEO-SIM renderers do not make the approximations listed above. The output from the high fidelity rendering kernel is a sequence of floating point, 2-D radiance maps for a given waveband or bands. These may then be played back at real-time rates for different applications.

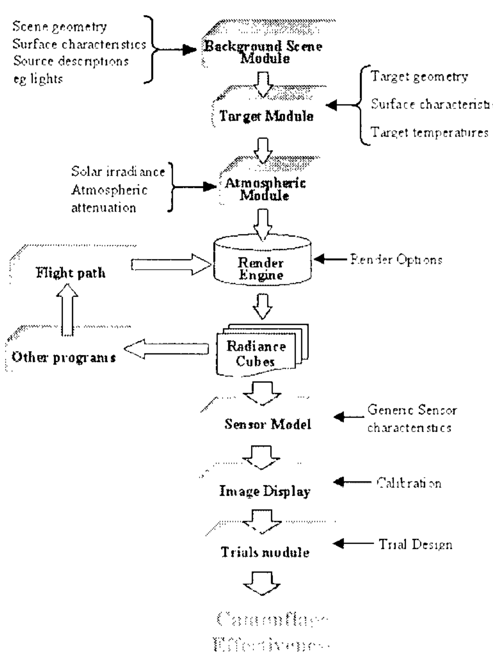


Figure 1 Block diagram of CAMEO-SIM components illustrating the data flow through the different processes.

5. ANALYTICAL VERIFICATION TESTS

CAMEO-SIM Version 1.0 is complete and is now undergoing verification and validation. A range of verification tests has been developed that exercise different elements of the high fidelity rendering equations implemented within CAMEO-SIM. All the tests have analytic solutions. Table 1 summarises the test results. A detailed description of each test is given in the following sections.

Test	Expected result	Calculated
Blackbody radiance	Blackbody Radiance = 42.89 (8-12.5 micron band)	42.89
Contrast in isothermal environment	Centre pixel radiance = 35.23 (8-12.5 micron band)	35.23
Shadowing and Blocking	a. Radiance of irradiated area = 5.1768 b. Radiance of blocked area = 0.0 c. Radiance of shadowed area = 0.0 (3-5 micron band)	a. 5.1768 b. 0.0 c. 0.0
Spectral calculations	Centre pixel radiance (3-5 micron band) = 1.49	1.49
Radiometric calculation of lighting effects	Radiance variation: Centre : 0.31831 edge : 0.0094248	Centre: 0.31806 edge: 0.0094239
Directional emission	Slope of radiance along centreline = 60.01 W m^{-2} pixel^{-1}	59.932 W m^{-2} pixel^{-1}
Multiple material Assignment on a texture	Blackbody radiance = 8.975 Grey body radiance =4.4875 (3-5 micron band)	Blackbody radiance = 8.975 Grey body radiance = 4.4875
Bi-directional reflectivity	Illuminated pixel radiance = 2.3	2.3
Small target rendering	Integrated facet radiant intensity = 1.806 W sr^{-1} (3-5 micron band)	1.813 W sr^{-1}

Table 1 Summary of validation test results. All values are W m^{-2} sr^{-1} unless otherwise stated.

5.1. Blackbody radiance tests

The purpose of this test was to ensure that the blackbody radiance is calculated correctly. A one metre square uniformly textured facet was created and the temperature of the facet set to a known value. The line of sight of the observer was centered and perpendicular to the facet. The radiance of a perfect blackbody was calculated and compared with the value computed within CAMEO-SIM.

5.2. Contrast in an isothermal environment

The purpose of this test is to ensure that the correct radiance contrast is predicted for isothermal vacuum, radiometric environments.

The skyshine radiance terms are set to constant values. A one metre square surface is defined to be a perfect diffuse reflector and the line of sight of the observer is centered and perpendicular to the facet. The radiance of the square is calculated and compared with the value computed within CAMEO-SIM.

5.3. Calculation of shadowing and blocking

Blocking is the rendering process that ensures parts of the object that are not visible to the observer due to obstruction by another part are correctly accounted for. Shadowing is the rendering process that ensures parts of the object do not reflect the point sources if they are obscured from it by other parts. This test has been designed to ensure that the blocking and shadowing algorithms are working accurately. The geometry for this test is shown in Figure 2 which shows two square plates with the lower plate 100% diffuse reflecting and the top plate black and at zero Kelvin. The observer and sun are at 45 degrees to the geometry. The radiance of the illuminated pixels in the image is:

$$N = Q\,\rho/\pi \qquad (1)$$

where:

N is the radiance in W m^{-2} sr^{-1}

Q is the normal incident irradiance W m^{-2} = solar irradiance x cosine of incidence angle

ρ is the diffuse reflectance of the lower plate

The solar irradiance is set to a fixed value. The radiance of the shadowed, blocked and irradiated areas is calculated and compared with the values computed within CAMEO-SIM.

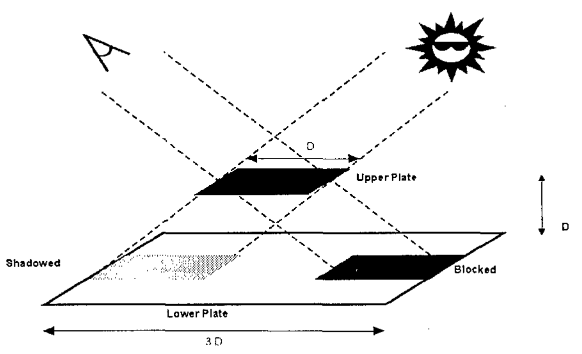


Figure 2 Diagram showing the geometry used to verify the blocking and shadowing computations.

5.4. Spectral Calculations

The purpose of this test specification was to verify that the spectral integrations were being calculated accurately. To test this a defined solar spectral irradiance was used to illuminate an artificial spectral material being observed with a spectrally selective sensor.

The spectral variation in the material properties, the light intensity and the sensor response is defined. For the general case, the in-band reflected radiance between the upper and lower wavelengths is given by:

$$N_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} \frac{J(\lambda)}{s^2} \cos\theta_i . \theta(\lambda) . \rho''(\lambda) . d\lambda \qquad (2)$$

where:

$N_{\delta\lambda}$ = in band radiance

θ_i = incidence angle between source and reflector

$J(\lambda)$= source intensity (W sr^{-1})

$\theta(\lambda)$ = sensor spectral response

$\rho''(\lambda)$ = spectral bi-directional reflectivity

s = distance to the source

5.5. Radiometric calculation of lighting effects

The purpose of this test was to verify that the radiometric effects of light sources are being accurately represented. The geometry of the test is shown in Figure 3a and a plot of computed (red line) and rendered radiance is shown in Figure 3b, together with the difference between the computed and rendered radiance. It must be noted the analytical solution assumes radiant intensity is at the pixel's centre, but the image's radiant intensity is super sampled across a pixel. This will introduce a small difference to the analytical solution.

5.6. Directional emission of uniformly textured and heated spheres

This test verifies that the second pass renderer is accounting for the directional emissivity correctly when the object is nominated as having directional optical properties.

Two uniformly textured spheres of 2m diameter are set to a known temperature. For one of the spheres, the vertex normals are equal to the facet normal and for the other, an appropriate angle is chosen for generating the vertex normals. Therefore, in the test both flat faceting and vertex normal interpolation in the second-pass renderer are tested. The variation in pixel radiance from the centre of the sphere to the outside edge should vary linearly (for the vertex normal interpolated sphere, and approximated with a stepped variation for the flat facet sphere.

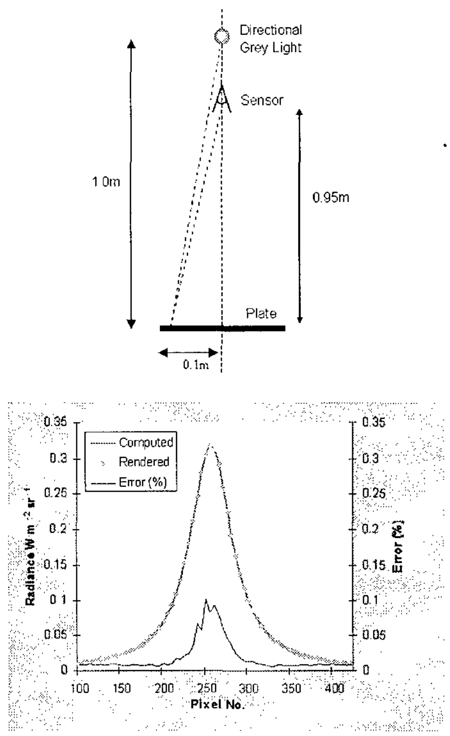


Figure 3 a) Lighting effects geometry. b) graph of computed and predicted radiance as a function of pixel position.

5.7. Textured heated billboard for testing multiple material assignments on a texture.

The purpose of this test is to ensure that textures that have been classified using multiple material associations and transparency are interpreted properly by CAMEO-SIM. To test this aspect a heated non-uniformly textured billboard with a transparent section is rendered. A 256 x 256 texture image containing two rectangles and a transparent region is created. One rectangle is classified as a blackbody perfect diffuser and set to a known temperature. The other rectangle is set to be a greybody perfect diffuser at the same temperature. A typical image expected from this test is shown in Figure 4.

5.8. Bi-directional reflectivity of uniformly textured and heated spheres.

The purpose of this test was to verify that CAMEO-SIM is interpreting the bi-directional reflectance function correctly.

To keep the solution to the BRDF problem analytically tractable a BRDF file was used that represents a grey semi-specular retro-reflecting BRDF such that

$$BRDF = \frac{1}{\cos(\theta)} \qquad \theta \leq 30\,\text{deg}$$
$$BRDF = 0.0 \qquad \theta > 30\ \text{deg}$$

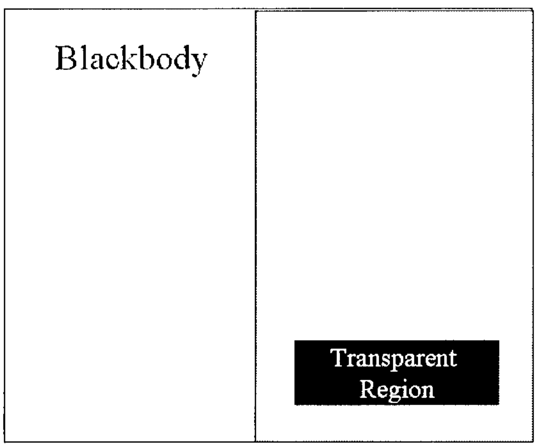


Figure 4 Schematic of the image produced by the textured heated billboard test.

where θ is the angle of incidence. Two spheres are created: for one sphere the vertex normals are equal to the facet normal and for the other sphere an appropriate angle is chosen for generating the vertex normals. The line of sight of the observer is set to view the spheres from above with the sun position above the observer. A typical image in which the illuminated pixels have a nearly constant radiance across their diameters is shown in Figure 5.

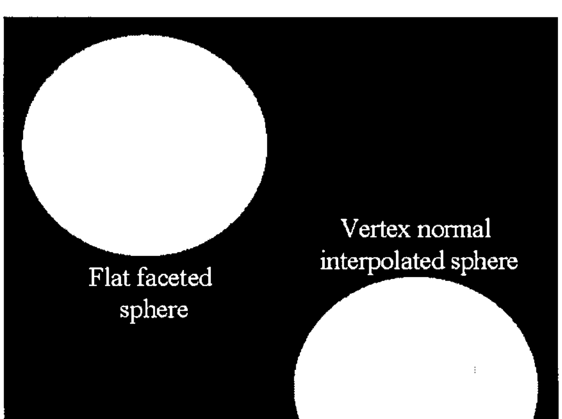


Figure 5 Image resulting from the bi-directional reflectivity test.

5.9. Small target rendering

The purpose of this test was to ensure that CAMEO-SIM is treating small targets to an acceptable accuracy; an essential requirement for simulating potentially sub-pixel targets. To test this requirement an identical sphere to that used in the BRDF test is rendered against a simple uniform background. The geometry of the test case is shown in Figure 6a, and the image formed for this test case should be similar to that shown in Figure 6b. The predicted integrated facet radiant intensity is 1.806 W m^{-2} sr^{-1}. The CAMEO-SIM integrated facet radiant intensity is 1.813 W m^{-2} sr^{-1} - a percentage difference of 0.39%.

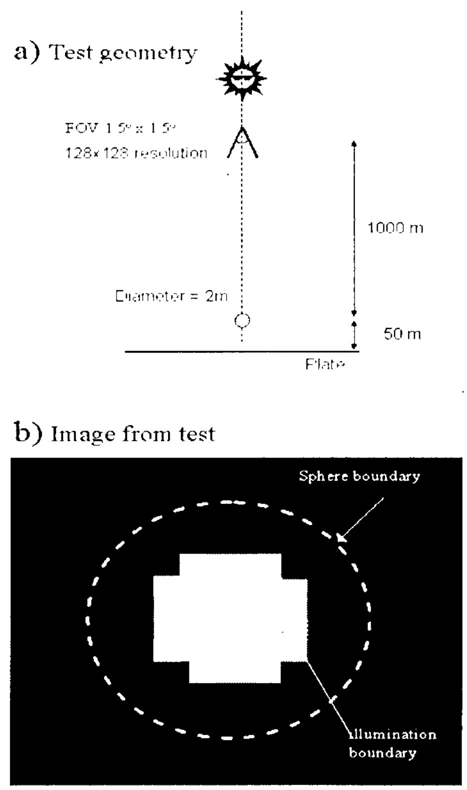


Figure 6 a) Geometry used to carry out the small target test. b) A typical image produced by the test.

5.10. Fit for purpose imagery

The verification tests have shown that CAMEO-SIM is computing the correct values. However rendering times are excessively long if the complete solution is calculated - especially for a complex structured scene. CAMEO-SIM was designed therefore to render images at different levels of fidelity, for different applications - such that the imagery is 'fit for purpose'.

Some example images for a clear day, visible band, generated at different levels of fidelity are shown in Figure 7. These images were created using three-dimensional models of trees constructed from triangular facets. No sensor effects have been added to the images.

Similar images can be created for different wavebands including visible, 3 - 5 micron and 8-12 micron band (Figure 8). A subjective analysis of the above images shows that the significance of different effects varies with waveband and with the weather condition - as expected. For example, on a cloudy day the hard shadows from the sun are not relevant.

Shadows appear to have a more significant effect in images of wavebands < 5 microns than for 8-12 micron band. In the lower wavebands the 'soft' shadow effects produce the three-dimensional effects of shadows on trees which appears to have a large effect on the contrast structure within the image, but this imposes a heavy computational load on the renderer.

Directional reflectance effects give rise to glints and cause more structure to be visible within the object - this is going to have a very significant effect on the spatial contrast structure within the image.

The image in Figure 9 shows the result of differencing and histogram equalising a 'low' fidelity and a 'high' fidelity image. Clearly there are large differences that could contribute significantly to errors in target conspicuity. For an image to be 'fit for purpose' the errors shown in the difference image must be insignificant for that particular application.

When viewed through a sensor the image resolution will be degraded and hence a lower level of fidelity may be acceptable. In addition the 'real world' is inherently variable, so the images only have to be accurate within the limits of the natural variations whilst still capturing the spatial and spectral structure.

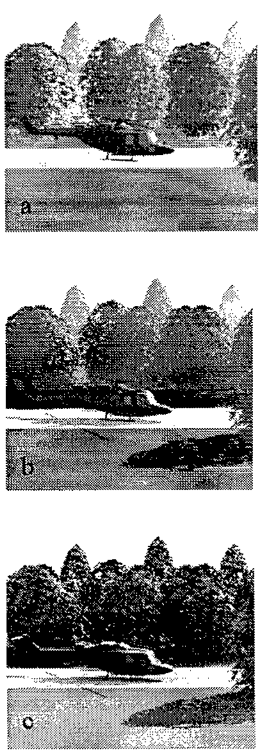


Figure 7 Example images rendered to different levels of fidelity: a) all surfaces diffuse, b) hard shadowing added, c) hard and soft shadowing plus BRDF characteristics applied to the aircraft.

6. VALIDATION

6.1. Issues

The issues surrounding the validation of any piece of simulation software are often complex and CAMEO-SIM is no exception. Furthermore, the fact that CAMEO-SIM aims to physically represent the real world, in many electromagnetic wavebands adds considerably to the difficulties, since we still have neither the basic databases nor the necessary understanding of what constitutes the real world. In addition, since the whole purpose of CAMEO-SIM is to represent scenarios that may not exist or are impossible to document, there may in fact be no equivalent real world. This can be illustrated at the simplest level by considering the geometry and culture that are used to describe a scenario. It is possible to achieve an exact match with the terrain geometry by using detailed map information, but it is impossible to achieve exactly the same geometry for the culture present in that terrain (eg tree structure). This means that validation methods that assume there is some real world database of measurements that can be directly compared with the output from the simulation cannot work. The validation processes that we are using are, as a result, somewhat more abstract and involve three separate approaches. Firstly, to use highly simplified scenarios that can be both synthesised within CAMEO-SIM and measured.

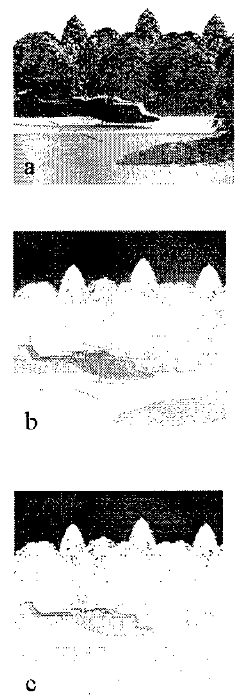


Figure 8 Examples of images generated in different wavebands: a) visible band, b) 3 – 5 μ, c) 8 – 12 μ

Figure 9 Histogram equalised difference between a low fidelity and a high fidelity image with identical geometry.

These move one step away from the basic analytical verification tests described in section 5. Secondly, we are examining whether the statistics of the imagery produced by CAMEO-SIM are consistent with the statistics of real world images. Finally, since the main use of this tool is for camouflage assessment we will use it to reproduce a real-world trial. This will assess whether the observer performance, using the synthetic imagery CAMEO-SIM generates, corresponds to the performance actually measured in the field. Each of these validation approaches is described in more detail below.

6.2. Simple Imagery Validation

None of the scenarios used in the tests described section 4 were real. The next step therefore is to exercise CAMEO-SIM with imagery that is more realistic. We plan to conduct a series of trials involving imaging a simple object viewed against a uniform background. The object is a metal step-like structure and is shown in Figure 10. The object is sufficiently complex to enable us to exercise both the radiosity and ray tracing processes within the software. Radiation will be reflected from the riser of the step down onto the lower step, the object will generate shadowing, different areas will heat up differentially, etc. It will be placed in the open and viewed by different sensors looking down into the "step" area. Imagery will be gathered in the visible band, MWIR, and LWIR under different conditions. The same scenario will be constructed within CAMEO-SIM using the measured geometry and surface material properties as well as metereological data.

Comparisons will be made between the in-band radiance values measured on the real object under different conditions and the equivalent values calculated within CAMEO-SIM using different rendering fidelities.

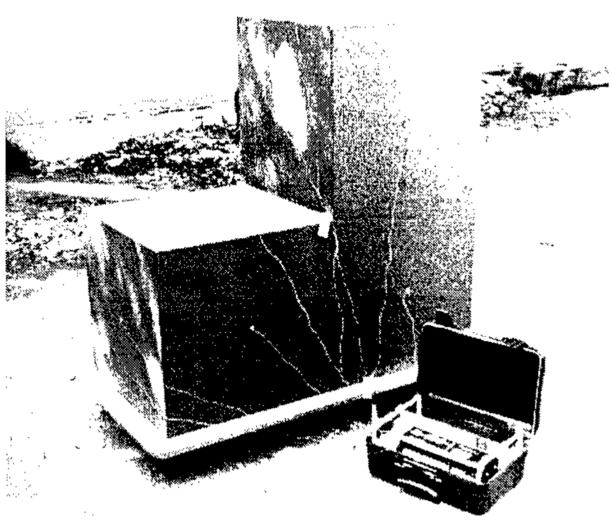


Figure 10 Photograph of the step object to be used in validation trials. The photograph also shows how the object can be instrumented with thermocouples for temperature measurement. (Lighter patches in the image are shadows.)

6.3. Image Statistics Validation

Many image metrics have been proposed [2,3,4,5,6]. Ideally, pixel comparison would be the ultimate method of comparing real and synthetic images. However this would, excessively overspecify the accuracy required, not only because of the natural variations in the real-world, but also because it is often the case that the synthesized imagery does not correspond directly to any part of the real world.

Bivariate metrics which compare similar images, and which are used extensively in the field of image compression (7) cannot be used because it will be impossible to exactly recreate the geometric structure of the real world in the synthetic image - and not necessary. Application of such metrics would indicate that there were large differences between the real and synthetic images, but these differences are not meaningful for this application.

Univariate metrics based on statistics of a single image are more appropriate as an 'image quality' metric. However first order statistics, such as mean and standard deviation are not an appropriate measure for the spatial structure in an image because two totally different images can have the same first order statistics.

Similarly second order statistics, such as the power spectrum, do not completely describe natural images. However, it is clear that if our simulation tool is not even capturing the first order statistics of the real world it has questionable validity. To illustrate this we provide here a comparison we have carried out between the colour characteristics of real world images and equivalent synthetic ones (using a visible-band precursor to CAMEO-SIM called CAM-SIM). A set of real world images obtained by a photographic colorimetric method (8) provided the necessary data for the real world. These were obtained during a trial in 1982 in Southern England. The scenario consisted of open grass fields with scrub and woodland clumps. There were no man-made buildings present in the images although a portion of the image was occupied by a military vehicle. Images were captured on different summer days and at different ranges from 0.5km to 3km. A similar scenario was constructed using CAM-SIM. Colour statistics were collected for the two types of image and the resulting histograms are shown in Figure 11. It is clear that the mean colour, expressed as chromaticity, of the two sets of imagery is similar, but that the distributions and ranges of the synthetic and real imagery are quite different. For certain applications these differences may be critical. Similar comparisons on a range of first and second order statistics are planned for CAMEO-SIM.

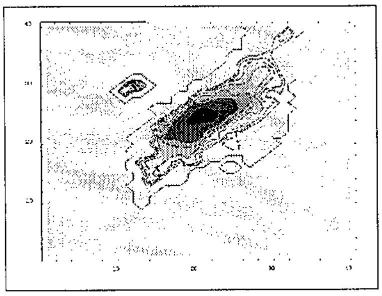
Higher order statistics which can capture phase information are likely to be the most appropriate metrics to investigate. However these are complex and hence difficult to interpret and apply. Certain types of Neural networks (Independent Component Analysis networks) naturally capture some of the features of higher order statistics after training. These networks can be trained on real imagery and then used on synthetic images to find if the same characteristics are detected. Therefore it is believed that neural networks would be an appropriate statistical solution for this project.

This work will continue and different metrics used to analyse the synthetic image fidelity so that appropriate images are used for different applications.

6.4. Performance Validation

The third element of the validation programme will involve comparisons of performance. The aim is to reproduce a real trial using imagery generated by CAMEO-SIM.

A flight trial was conducted in 1974 to compare a light grey camouflage scheme with a dark grey /green scheme on UK Royal Air Force strike aircraft. The comparison was made by flying aircraft painted in the two schemes against ground based observers under a variety of meteorological conditions and recording the detection ranges obtained. Observation was made with the unaided eye and with magnifying sights (X5 and X10). The nature of the trial required the aircraft to fly accurate straight-line tracks of about 20kms on a variety of headings and at low level.



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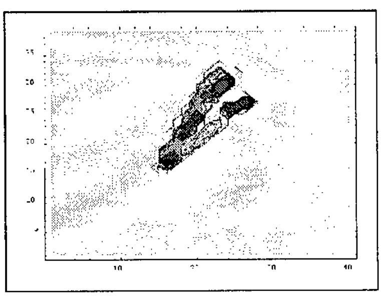

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Figure 11 CIE (x,y) chromaticity histograms. a) distribution for real imagery. b) distribution for synthetic imagery.

The following conditions and variables were selected:

1. Observers used unaided viewing, x5 and x10 optical sights.
2. Limited search - the observers knew the approximate height and direction of approach but were not accurately laid–on. Search using the magnifying sights was within the field-of-view along a fixed sight-line
3. The trial was conducted under three types of sky condition – clear sky, 2/8-4/8 broken cloud and uniform overcast. Visibility was at least 10km.
4. Three relative aircraft/observer/sun positions were studies: sun directly behind the observer as he viewed the approaching aircraft, sun at 60° to the approach path shining onto the front of the aircraft and sun at 45° to the approach path shining onto the rear of the aircraft.
5. Approaches were made head-on to the observers and to cross 1000m to left and right of the observers. Approaches began 20km from the observers.
6. Aircraft were 200m above ground level, speed 300 knots.

There are 27 possible different combinations of the above variables, but because sun position is not relevant under a uniformly overcast sky and crossing to left and right was not required when the sun was directly behind observers the actual number of different conditions reduces to18. Each aircraft made 6 approach runs per condition tested – 18 sorties were required to complete the trial.

Both experienced and inexperienced observers were used. Experienced observers had a visual acuity of 6/6 or better with normal colour and binocular vision. Inexperienced observers were tested using a car number plate reading test at a range of 30m.

Cloud conditions generally and in the direction of view were noted. Colour of background sky was estimated by comparison with a set of Munsell colour analysis charts. Background sky luminance was measured with a Weston Master 1V light meter.

Detection ranges were obtained by timing each approach. The observers, with stop watches were given a signal as the aircraft crossed the IP and started their watches, they then stopped their watches individually upon detecting the aircraft. During every approach the aircraft was also timed between two timing marks enabling its ground speed to be accurately determined. This ground speed, the distance between the observers and the IP, and the time to detection were then used to calculate detection range.

The validation exercise will consist of a laboratory simulation of this trial. Clearly attempting to reproduce exactly the same conditions is impossible therefore a much simplified trial design will be used. Visible band image sequences of the scenario containing aircraft in the two different camouflage schemes will be generated using CAMEO-SIM. These will be played back to observers viewing a calibrated colour monitor from a fixed distance (images are rendered to be viewed from a predetermined distance) as shown in Figure 12. Any one sequence will consist of an image of an aircraft "painted" in one of two colours, which will fly along a randomised track towards the observer. The observer task will be to press a mouse button when the aircraft is detected and then to designate the aircraft location on the screen using a cursor.

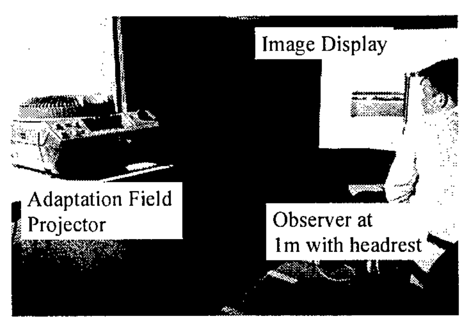

Figure 12 Experimental arrangement. The observer is maintained at a fixed distance from the calibrated display used to present the test imagery. An additional projector is used to provide a controlled adaptation state.

Response time will provide the detection range just as in the real trial. Additionally, this experiment will provide information on accuracy of designation. These data will be compared with the results from the actual trial. Because there are so many differences between the real and the simulated trial conditions only relative performance will be compared. Observers will be screened for colour vision and acuity prior to taking part in the trial. A mean level of adaptation will be maintained by surrounding the display with a white screen if necessary.

7. CONCLUSIONS

CAMEO-SIM can generate imagery between 0.4 and 14 microns to different levels of fidelity, to allow a trade-off between accuracy and rendering time. The software has undergone a range of verification tests to show that the correct values are computed. A programme of validation is now under way to ensure that meaningful results are obtained using the software tools. This programme will address three different aspects of the synthetic imagery – statistics, real-world comparisons and performance prediction. Research work is in progress to quantify the significance of different effects such as shadows, in different wavebands. The functionality of CAMEO-SIM will be extended as part of an ongoing research programme to include multi-processor rendering capability, and simple multi-spectral image display, moving sensors and thermal shadows.

8. ACKNOWLEDGMENTS

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